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(54) High voltage power supply

(57) A compact high voltage power supply includes a high voltage transformer 4 with individual concentric secondaries S1, S2, . . . , connected to form a ladder network with two series-connected assemblies of diode rectifiers R and R' respectively located on corresponding sides of the transformer winding.

Next-adjacent secondaries S1, S2, . . . , are wound from the same side of the winding space but in an opposite winding sense, and each secondary comprises an odd plurality of layers. This provides a high voltage transformer-rectifier arrangement without cross-connection of the diodes in which the peak and alternating voltages across the interwinding insulation are optimally reduced and the smoothing effect of stray capacitics is enhanced.

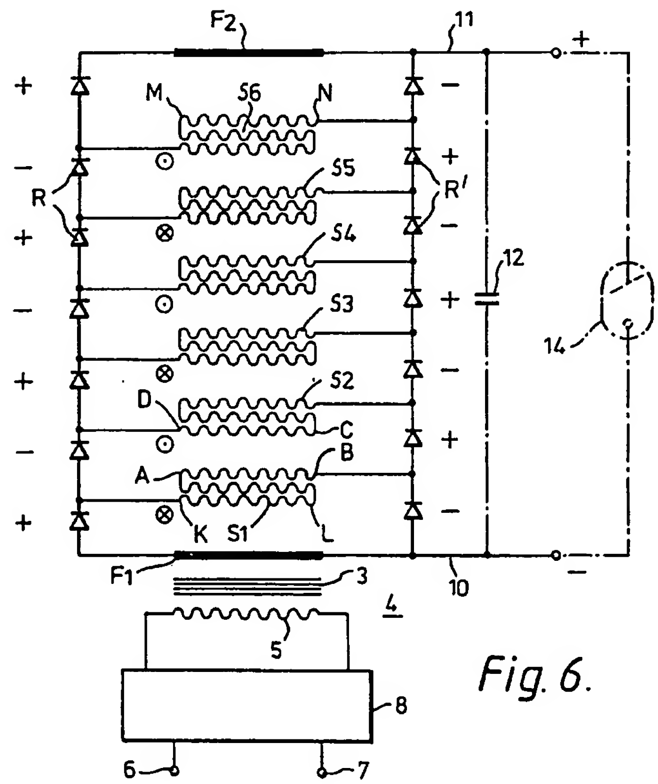

Fig. 6.

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The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.

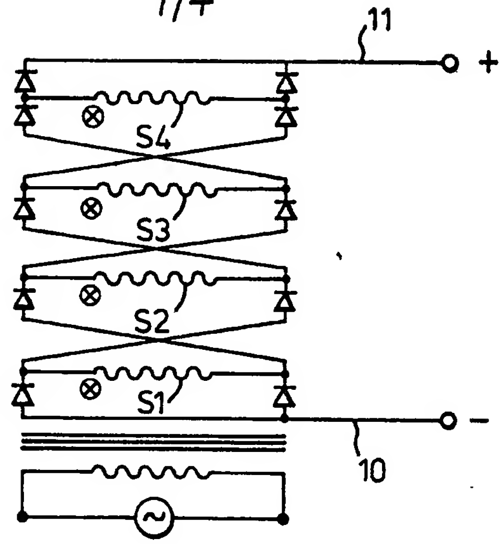

Fig. 1.

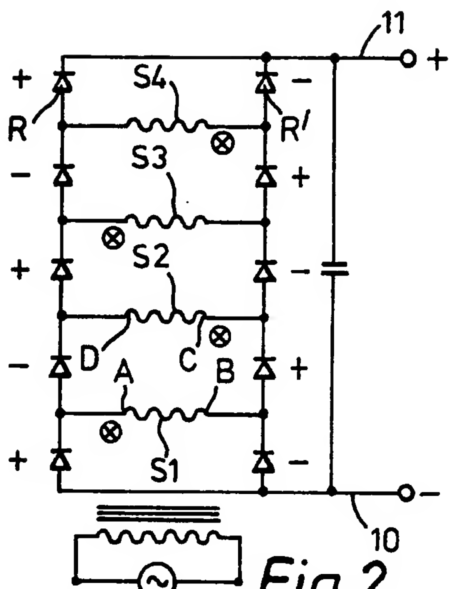

Fig. 2.

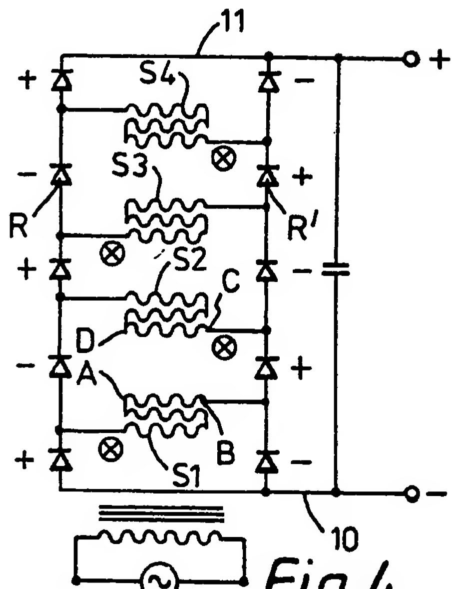

Fig. 4.

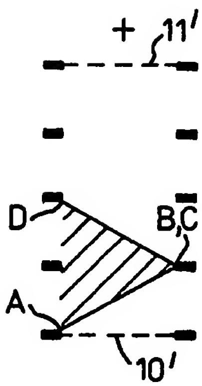

Fig. 3a.

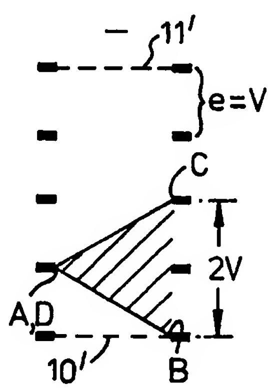

Fig. 3b.

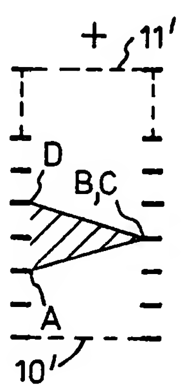

Fig. 5a.

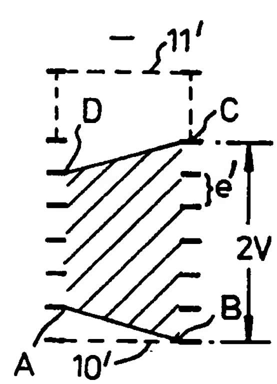

Fig. 5b.

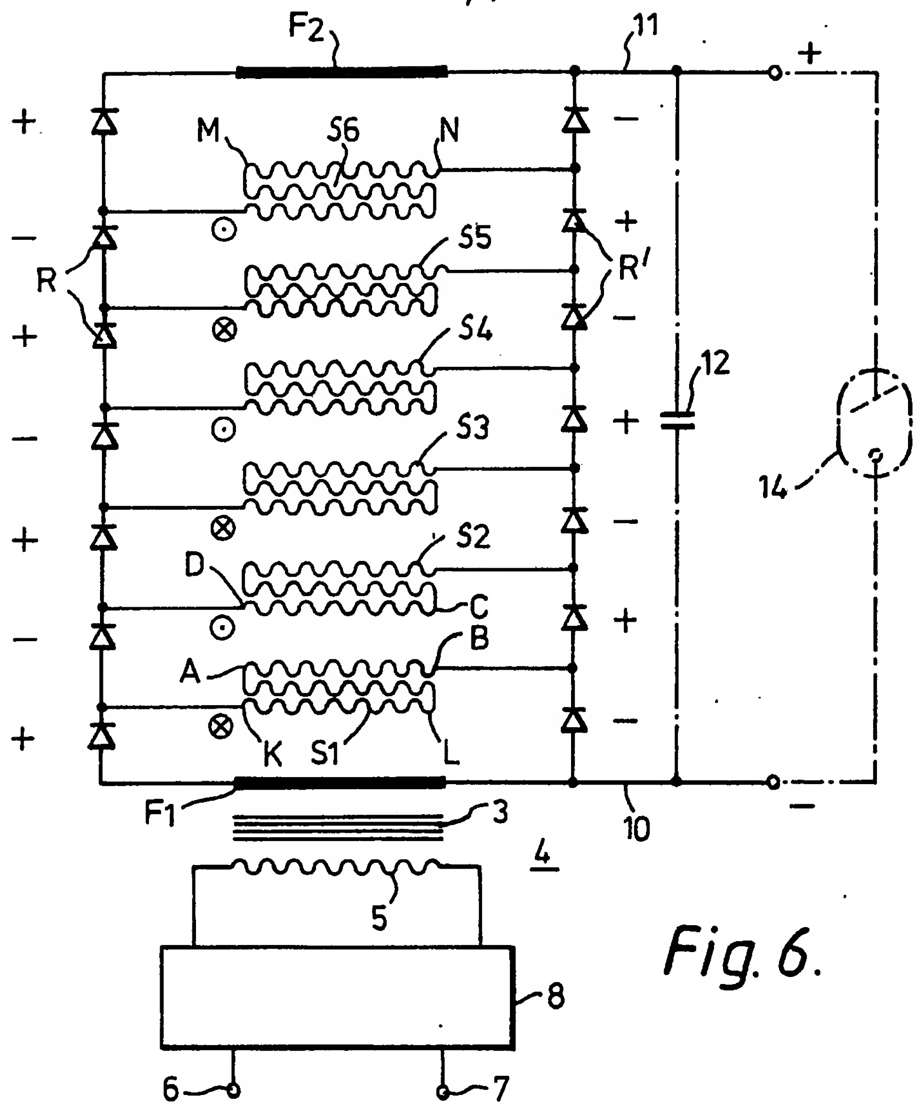

Fig. 6.

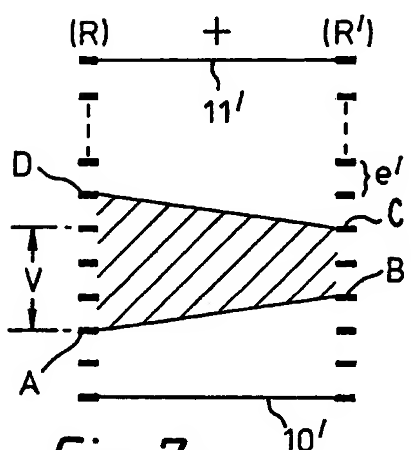

Fig. 7a.

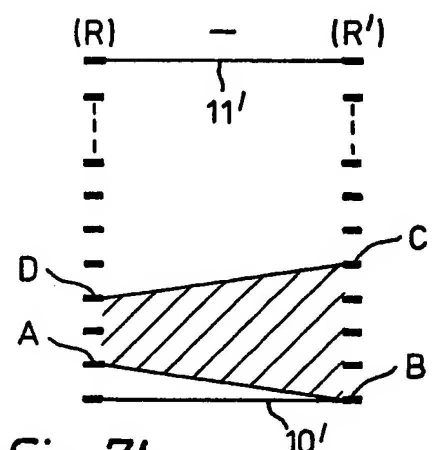

Fig. 7b.

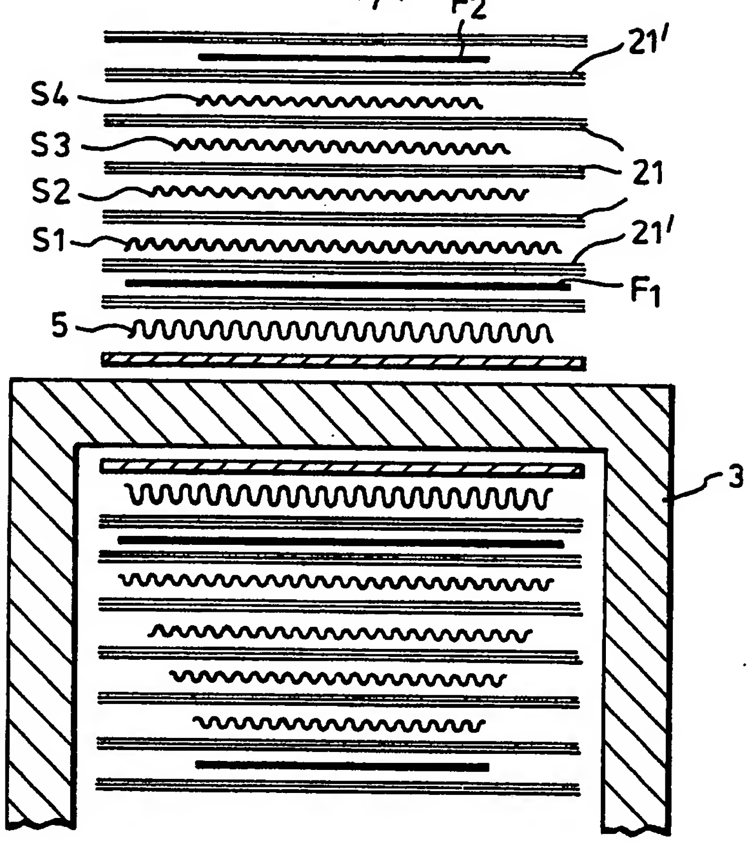

Fig. 9.

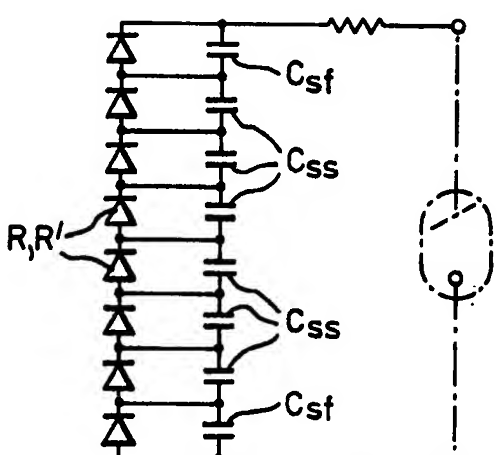

Fig. 8.

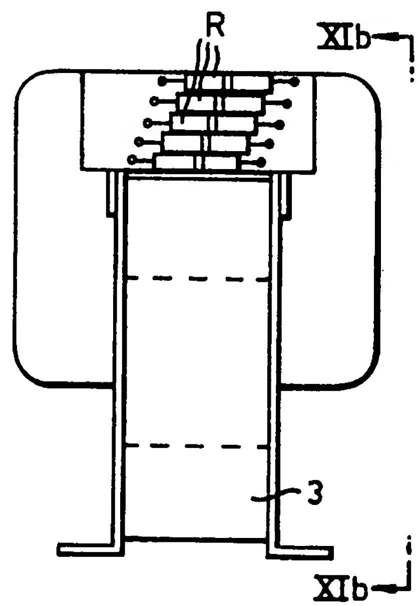

Fig. 11a.

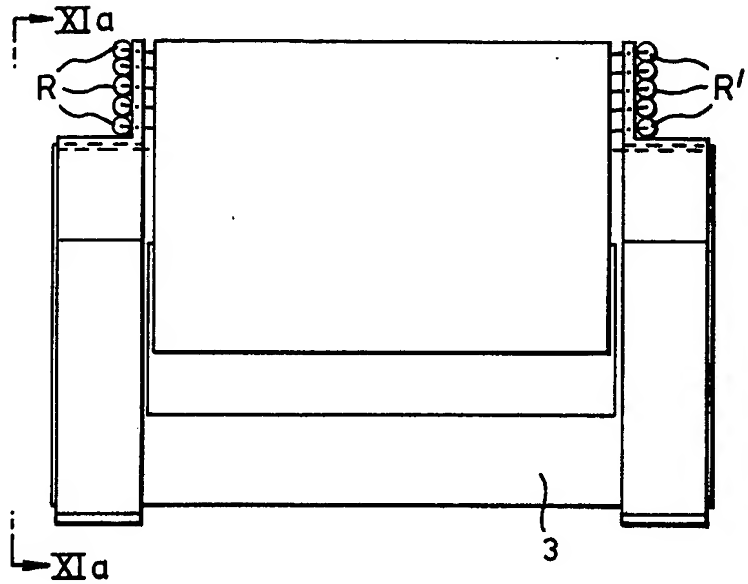

Fig.11b.

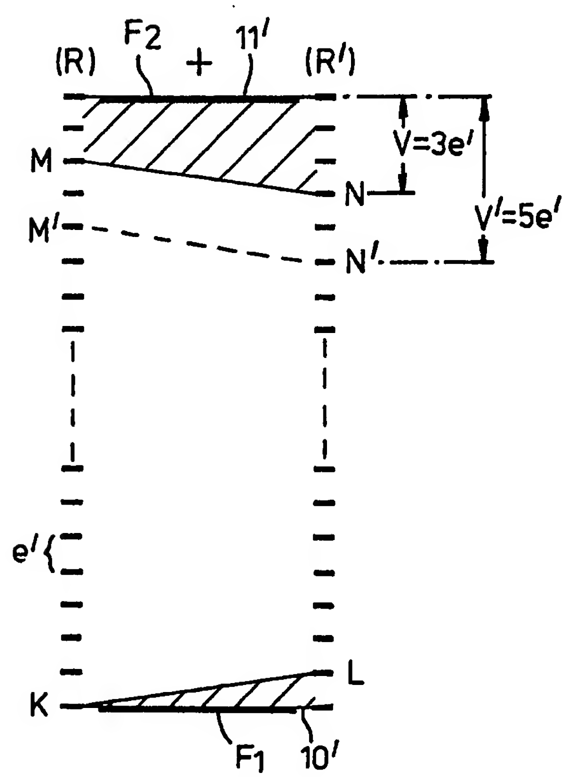

Fig.10a.

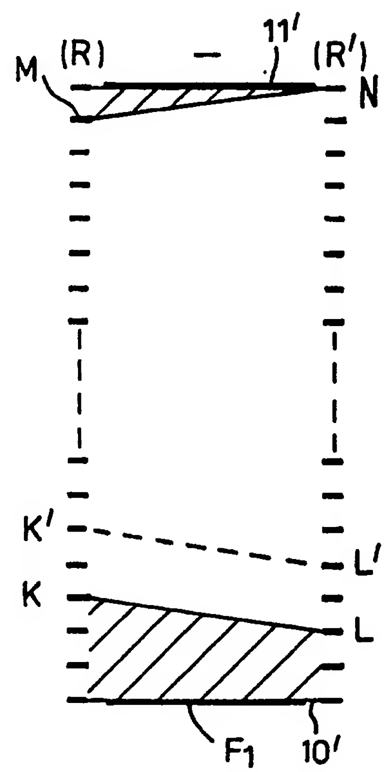

Fig.10b.

SPECIFICATION
High voltage power supply

The invention relates to a high voltage power supply including a transformer and rectifier assembly in which the high-voltage secondary of the transformer comprises a plurality of concentric individual windings and each end of each secondary winding is connected via a respective rectifier to a corresponding end of the next adjacent winding or to a high voltage supply connection so that the assembly provides a full wave rectified output. Such a high voltage power supply will be referred to hereinafter as a high-voltage power supply of the kind specified.

A high voltage power supply of the kind specified is disclosed in Figure 13 of U.K. Patent Specification Number 1,090,995, and is illustrated herein in Figure 1, in which each secondary winding S1, S2, S3, S4 comprises a single layer winding and the rectifiers are cross-connected to opposite sides of the winding space. The arrangement therein disclosed has the advantage that each interwinding stray capacitance is bridged in operation by a uniform quasi-steady rectified voltage enabling it to perform the function of a smoothing capacitance, and permitting less insulation to be used and to be of a kind having a higher dielectric loss factor and therefore less costly. However, the need for the rectifiers to be connected across from one side of the winding to the other causes difficulty in the provision of sufficient insulation, and causes the assembly to be rather bulky.

It would be advantageous therefore if each rectifier were connected between those ends of adjacent windings which are disposed on the same side of the winding, and this can be done if the adjacent secondary winding layers are wound from opposite sides of the winding area as illustrated in Figure 2. In this diagram those rectifiers which conduct during a first half cycle are labelled with a plus sign and those which conduct during the other half cycle are labelled with a minus sign.

Figures 3a and 3b are voltage diagrams illustrating the potential distribution along the windings S1 from A to B and S2 from C to D at the peaks of the first and second half cycles respectively. Each winding layer generates a peak voltage indicated by e.

Thus during a first half cycle the end A of the winding S1, will be at the negative high voltage supply potential 10′, the end B of S1 and the end C of S2 will be at the same potential *e* above the negative high voltage connection and the end D of S2 will be at a potential 2e relative to the end A of S1. Thus, as illustrated in Figure 3a by the shaded region, the insulation between the windings S1 and S2 will be subjected to an electric field ranging from zero to twice the voltage V provided by a single winding. At the peak of the other half cycle, illustrated by Figure 3b, the electric field distribution across the interwinding insulation is laterally reversed. Thus during a cycle of alternation, the insulation between the ends A and D and between the ends B and C of the secondaries S1 and S2, is subject to an alternating potential difference of 2e peak to peak and must not only be sufficiently thick to withstand this voltage but must also have a low dielectric loss factor because of the large alternating field component in these regions.

It may be thought that the arrangement of Figure 2 could be improved by winding each individual secondary S1, S2, . . ., as several layers, e.g. three layers as illustrated in Figure 4. However, corresponding voltage diagrams in Figures 5a and 5b show that very little change occurs in the demands made on the interwinding insulation.

Again the shaded region indicates the interwinding potential distribution, and is assumed that each layer develops a voltage e′ between the ends thereof. Since each winding is shown as three layers, the voltage V to be developed by a secondary winding will be 3e′ but it will be assumed for comparison that an individual secondary will generate the same voltage V in the various cases discussed, therefore the value of e in the arrangement of Figure 2 will be three times the value of e′ in that of Figure 4.

When the first half cycle is considered, see Figure 5a, the potential across the interlayer insulation varies from 2e′ between the ends A of S1 and D of S2 to zero between the ends B of S1 and C of S2 since the first 'plus' diode on the right in the figure provides a short circuit. In the other half cycle shown in Figure 5b, however, while the voltage between the end A of S1 and the end D of S2 only doubles to 4e′ which is still less than the voltage 2e for the circuit in Figure 2, the voltage between the end B of S1 and the end C of S2 will increase from zero to a value 6e′ which is twice the secondary voltage V = 3e′, and is in fact as great as in the case of the arrangement shown in Figure 2, and provides a correspondingly large alternating component. Since the amount of insulation present must be sufficient for the worst situation along the windings, the arrangement of Figure 4 will not permit any reduction in the cost of insulation either by reducing the amount or allowing a cheaper material with a higher dielectric loss factor to be employed. Furthermore the presence of a large alternating voltage component will reduce the charge storage effect available for smoothing purposes.

It is an object of the invention to provide an improved high voltage power supply of the kind specified in which the rectifier diodes are connected so as not to cross from one side of the winding to the other, while enabling less insulation to be employed at reduced cost.

According to the invention there is provided a high voltage power supply of the kind specified characterised in that next-adjacent windings are wound in the opposite winding sense starting from the same side of the winding, that each winding comprises an odd plurality of winding layers, and that for each pair of next adjacent

windings each rectifier is connected to the ends of the respective adjacent windings, which lie on the same side of the windings.

The invention is based on the realisation that by starting all the secondary windings from the same side of the winding region, and winding each secondary with an odd plurality of layers but in an opposite winding sense for each next-adjacent pair of secondaries, a winding arrangement is provided which, when connected to respective in-line connections of rectifiers at the corresponding ends of the windings, will result in a quasi-steady voltage difference being set up between the facing conductive areas of adjacent secondary windings, and which form the interwinding stray capacitance. In this way, the potential difference between adjacent windings can be reduced, thus reducing the amount of insulation required and, because the potential difference is quasi-steady in operation, this will permit a less expensive insulation material exhibiting a higher loss factor to alternating potentials, to be satisfactorily employed, and can enable a significant and useful capacitive smoothing effect to be provided.

An embodiment of a high voltage power supply in accordance with the invention is characterised in that an inductively open-circuit layer of electrically conductive foil is disposed adjacent but insulated from the inner surface of the innermost secondary winding and electrically connected to that high voltage supply conductor to which the ends of the innermost secondary winding are connected *via* respective rectifiers. The embodiment can be further provided with an inductively open-circuit foil layer disposed in insulated manner adjacent the outer surface of the outermost secondary winding and similarly connected to the other high voltage supply conductor. In this way corresponding stray capacitances are provided so as to bridge each of the rectifiers so as to provide protection from reverse breakdown in the event of a flash-over.

Preferably the successive secondary windings or foil layer of larger diameter is each made smaller in width, i.e. shorter in winding length, so as to present substantially the same conductive surface area to each next adjacent winding. In this way the corresponding shunt stray capacitances can be made substantially the same magnitude to equalise the reverse potential distribution across the rectifier diodes.

Preferably an even number of secondary windings are employed to ensure that the ripple component of the rectified output is mainly at twice the frequency of the alternating supply to the primary of the high voltage transformer thus facilitating smoothing.

An embodiment of the invention will now be described by way of example, with reference to Figures 6 to 11 of the accompanying drawings, of which:—

Figure 6 is a schematic diagram illustrating a high voltage power supply in accordance with the invention,

Figures 7a and 7b are voltage diagrams relating to the operation of Figure 6,

Figure 8 is an equivalent circuit of Figure 6,

Figure 9 illustrates the winding area of the transformer employed in Figure 6,

Figures 10a and 10b are further voltage diagrams relating to the operation of Figure 6, and

Figures 11a and 11b illustrates the construction of a transformer-rectifier assembly in accordance with the invention.

A high voltage power supply for supplying an X-ray tube and embodying the invention, is illustrated schematically in Figure 6, and comprises a high voltage transformer 4 whose primary winding 5 is fed with an alternating voltage suitably supplied either directly from a public supply mains *via* connections 6 and 7, or from conversion means included in the block 8, which provides an alternating supply at a frequency of several kHz from a source of direct current, such as an accumulator, or by rectification from the supply mains 6, 7. A higher excitation frequency will reduce output ripple and enable a smaller core 3 to be employed, thus saving weight.

The high voltage secondary of the transformer 4 comprises a plurality of concentric individual secondary windings S1, S2, . . ., and each end of each secondary winding is connected *via* a respective rectifier R or R′ of a corresponding series connection of rectifiers, to a corresponding end of the next adjacent winding or to one of two high voltage supply connections 10, 11, so that the assembly provides a full wave rectified output across an output smoothing condenser 12 to feed an X-ray tube 14 connected to the high voltage connections 10, 11. The smoothing condenser 12 may be small in value and may even be omitted when the excitation frequency is relatively high and the output current low, since the winding stray capacitance may then provide sufficient smoothing. This general form of high voltage power supply arrangement is sometimes referred to as a diode split staircase generator.

In accordance with the invention, next-adjacent secondary windings S1, S2, S3, . . . are wound in the opposite winding sense as indicated by the symbols $\oplus$ and $\ominus$, starting from the same side of the winding area, e.g. the left-hand side in Figure 6, and each winding comprises an odd plurality of winding layers. Only three winding layers are shown for each secondary, but for reasons given hereinafter it is preferable that a greater number of layers should be used. For each pair of next-adjacent secondary windings S1, S2, each rectifier R or R′ is connected to the ends of the respective adjacent windings which lie on the same side of the windings, e.g. in Figure 6 on the left and on the right, respectively.

Figures 7a and 7b are voltage diagrams illustrating the voltage distribution, shaded region, between the outer surface of winding S1 and the inner surface of the next adjacent winding S2 in the arrangement of Figure 6, and to which a conventional layer of insulation (not shown) separating the windings would be subject. It is

apparent from Figure 7a that at the peak of a first half cycle, the voltage between the end A of S1 and the end D of S2, will be 4e′, and that between the end B of S1 and the end C of S2 will be 2e′, where e′ is the voltage induced in each winding layer. At the peak of the other half cycle, Figure 7b, the sitautlon will be reversed. Thus it will be seen that the alternating component at each end of the insulation layer will only have a peak to peak excursion of 2e′, i.e. 2/3 V, where V is the voltage induced in each individual secondary winding, and the maximum voltage present across the insulation layer will be 4e′, i.e. 1 1/3 V. This compares favourably with the corresponding values of 2V and 2V, respectively, for the arrangement shown in Figure 4. This means that by only employing three winding layers in each secondary, the arrangement of Figure 6 can considerably reduce the maximum alternating voltage component across the insulation layer from 2V to 2/3 V and hence the dielectric losses, and can significantly reduce the peak value of the interwinding voltage across the layer. If a greater number of winding layers were employed in each secondary winding S1, S2 in the arrangement shown in Figure 6, the magnitude of the alternating voltage component will be correspondingly reduced to a smaller fraction of the secondary voltage V and the peak voltage between the windings will tend towards the value V.

Thus if, for example, 5 winding layers were employed, the alternating peak to peak excursion of 2e′ would only represent 2/5 V, and the peak interwinding voltage of 6e′ would represent only 6/5 V. Corresponding reductions would occur as the number of winding layers per individual secondary winding are increased. This is in contrast to the situation occurring in the arrangement of Figure 4 in which the corresponding values would remain unaltered with an increasing number of winding layers per secondary.

In experiments conducted on an example of a power supply in accordance with the invention employing individual secondary-windings each having several, for example 7, winding layers, it was found practicable to depart from the normal rule concerning the breakdown strength of insulation materials namely 3.1 V t/μ insulation for voltages of or above 500 V_{rms}, and to use values of from 16 to 20 Vt/μ satisfactorily with significant savings in cost, where t is the peak value of the alternating voltage and μ is the thickness of the insulation in μ metres.

It will be apparent that the facing surfaces of adjacent secondary windings together with the layer of insulation therebetween will form a capacitance, an interwinding stray capacitance, and as can be seen from Figures 7a and 7b, there will in operation be a significant direct component of electric field across the insulating layer indicating a corresponding amount of charge energy storage which can contribute to the smoothing of the rectified output. More important is the fact that the interwinding stray capacitances C_{ss} are each effectively connected across a corresponding pair of rectifiers R, R′, as illustrated in the equivalent circuit of Figure 8 in which the secondary windings are not represented. The presence of these capacitances can reduce the risk of damage to the corresponding rectifiers in the event of a flash-over in the rectified high tension circuit which can result in the application of a reverse voltage across the rectifiers, and if this is not equally distributed between the individual rectifiers, damage or destruction can result.

The rectifiers at each end of the ladder network and which respectively connect the first and last windings to a corresponding high voltage supply conductor, do not have an interwinding capacitance in parallel. External capacitors can be connected to provide protection for these rectifiers, however, protection can alternatively be obtained by arranging respective inductively open-circuit layers of electrically conductive foil F_1, F_2, adjacent the inner surface of the innermost secondary and the outer surface of the outermost secondary, and connecting each foil to the corresponding high voltage supply conductor 10, 11, which is connected to the adjacent winding *via* the rectifiers to be protected. The presence of the corresponding stray capacity is indicated in Figure 8 by C_{sf}.

Figure 9 illustrates the manner in which successive secondary windings are disposed concentrically one over the other within the winding cross sectional area of the transformer. For the sake of clarity only four secondary windings S1, S2, S3, S4, are shown in Figure 9. The primary winding 5 is wound first next to the central part of the core, followed, after an open circuit layer F_1 of conducting foil, in succession by the secondary windings S1, S2, . . ., the winding widths of which are made smaller in correspondence with the increase in the effective voltage of that winding as it is connected further up the series connection of rectifiers, relative to the potential of the core 3, and of its supporting bracket. In the arrangement shown, the core will be at or about ground potential as will the negative conductor 10 of the high voltage supply. In this way the risk of voltage breakdown between the ends of the secondary windings and the side portions of the core and supporting bracket will be reduced and can be minimised.

It should be noted that the invention is equally applicable to a high voltage power supply in which the positive high tension terminal is to be at or near the core potential, e.g. ground. In that case the connections of the rectifiers in Figure 6 would all be reversed so as to reverse the potential between the conductors 10 and 11.

It will be apparent from Figure 9 that the secondaries S1, S2, S3, . . ., are of successively greater diameter, and it is therefore convenient to arrange the dimensions such that the conductive surface area presented by each secondary winding to the next adjacent secondary winding, or foil when present, is of substantially the same

magnitude for all the secondaries. By using interwinding insulation 21, 21', having the same thickness and dielectric constant, all the interwinding stray capacitances can be made of substantially the same magnitude with the result that any reverse potential occurring under flash-over fault conditions will be divided equally between the various rectifiers. If, however, it should be necessary to use an interwinding insulation, say for layers 21', which has a different dielectric constant from that of the other layers 21, the stray capacitance can still be made the same by using an appropriately different thickness of material.

It should be noted that, if the foil layers F_1 and F_2 are employed to provide protective capacitances for the corresponding end rectifiers, the insulation layers 21' between the winding and the foil may have the same thickness as the interwinding layers 21. However, in addition, the insulating foils 21' must be of low dielectric loss because the potential across those layers will consist almost entirely of an alternating component as can be seen from Figures 10a and 10b. These figures represent voltage diagrams showing the voltage difference, shaded, between the respective foils F_1, F_2 and the corresponding facing surfaces KL of secondary winding S1, and MN of S2 as shown in Figure 6, during the first and the other half cycle, respectively. The voltage steps represent the voltage e' generated by each layer of the secondary winding as in the case of Figures 7a and 7b, and if a greater number of layers were used per secondary, the line MN in Figure 10a and the line KL in Figure 10b would be shifted away from the corresponding high voltage conductor potential 11' and 10', as indicated by the dashed line for 5 layers. Thus as the number of layers per winding increases so will the lines be more parallel to the axes 11', 10', when the diagrams are correspondingly scaled down to correspond to the same V.

Although the potential across the end stray capacitors C_{sf}, alternates between V and zero on alternate half cycles, each capacitor will nevertheless hold the charge applied at the peak of the wave and will behave as a reservoir capacity until the opposite peak occurs which reduces the charge to zero. In the embodiment of Figure 6 illustrated by Figures 10a and 10b, an even number of individual secondary windings are employed, and it will be seen from Figure 10 that the two capacitances C_{sf} will respectively store a peak rectified charge during alternate half cycles, and any corresponding ripple will be of twice the frequency of the transformer input. It will be apparent that the alternating voltages between the outermost surfaces of adjacent pairs of secondary winding will substantially cancel for an even number of secondaries, enabling the capacitances C_{ss} and C_{sf} in series to act as a useful, and under favourable conditions the entire smoothing capacity.

When an odd number of secondary windings are employed the situation is somewhat different. In that case both capacitances C_{sf} are charged during one half cycle and are discharged during the other, and the alternating voltage between the outer surfaces of one of the secondaries will remain uncancelled. The effect of this is for the transformer-rectifier assembly to tend to generate a slightly greater amount of ripple with a significant fundamental component. This need not be important when a sufficiently large reservoir condenser 12 is employed. However, the use of an even number of individual secondary windings is to be preferred.

The compact form of a high voltage power supply in accordance with the invention can be seen from Figures 11a and 11b which shows a transformer-rectifier assembly using non-crossing diodes and embodying the invention.

While a high voltage power supply for supplying an X-ray tube has been described herein by way of example, a high volage power supply in accordance with the invention may be usefully employed to supply any high voltage low current device, such as a cathode ray tube, an X-ray image intensifier, or an ionisation detector, or a radar high coltage supply, and can be advantageously used in portable equipment.

CLAIMS

1. A high voltage power supply including a transformer and rectifier assembly in which the high-voltage secondary of the transformer comprises a plurality of concentric individual windings and each end of each secondary winding is connected via a respective rectifier to a corresponding end of the next adjacent winding or to a high voltage supply connection so that the assembly provides a full wave rectified output, characterised in that next-adjacent windings are wound in the opposite winding sense starting from the same side of the winding, that each winding comprises an odd plurality of winding layers, and that for each pair of next adjacent windings each rectifier is connected to the ends of the respective adjacent windings, which lie on the same side of the windings.

2. A power supply as claimed in Claim 1, characterised in that an inductively open-circuit layer of electrically conductive foil is disposed adjacent the inner surface of the innermost secondary winding and electrically connected to that high voltage supply conductor to which the ends of said innermost secondary winding are connected *via* respective rectifiers.

3. A power supply as claimed in Claim 1 or Claim 2, characterised in that an inductively open-circuit layer of electrically conductive foil is disposed adjacent the outer surface of the outermost secondary winding, and electrically connected to that high voltage supply conductor to which the ends of said outermost secondary winding are connected *via* respective rectifiers.

4. A power supply as claimed in any one of the preceding claims, claims, characterised in that successive said secondary windings of larger diameter are made smaller in width so as to

present substantially the same magnitude of conductive surface area to the next adjacent winding.

5. A power supply as claimed in any one of the preceding claims, characterised in that the high voltage secondary of the transformer comprises an even number of individual secondary windings.

6. A high voltage power supply including a transformer and rectifier assembly substantially as herein described with reference to Figures 6, 7, 8, 9, 10 and 11 of the accompanying drawings.

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